Evaluation of the TOPEX/POSEIDON Altimeter System Over the Great Lakes

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Short title: TOPEX/POSEIDON Great Lakes Evaluation

Abstract

The TOPEX/POSEIDON altimeter measurement system is evaluated over the Great Lakes. Using in situ lake level measurements, the temporal variations in lake level are removed from the altimeter measurements, thus permitting the performance of the altimeter system to be assessed. For the NASA altimeter, the root mean square (RMS) scatter of the residuals is 4.4 centimeters (cm). This places an upper limit on the error budget of the altimeter system, excluding ocean tides and inverse barometer effect. Although there is no significant long-term drift in the residuals, there is a 56-day variation that appears to be correlated with the synodic period of the satellite. When the model-derived wet tropospheric correction is substituted for the TOPEX Microwave Radiometer (TMR) correction, the RMS error increases significantly, possibly resulting in an annual cycle of a few centimeters. Evaluation of the ionospheric correction indicates that the dual-frequency correction provides an average improvement of 1.3 cm over the DORIS correction. A comparison of the NASA and CNES orbits shows that the CNES orbit produces slightly smaller residuals. Although there are insufficient data to directly assess the CNES altimeter, the relative bias between the NASA and CNES altimeters is estimated to be -18 cm, with the NASA altimeter measuring short,

Introduction

The evaluation of spaceborne altimeter systems has typically focused on their performance over the oceans. Techniques, such as crossover analysis, suffer from limitations because of uncertainties in tidal models and oceanographic variability. Although an extensive amount of data are available for these evaluations, they provide only a general upper limit on the error in the altimeter system. In this paper, we take a different approach. Rather than evaluating the TOPEX/POSEIDON measurement system over the ocean, our analysis looks at its performance over the Great Lakes.

Evaluating an altimeter system over lakes has a number of advantages. Lakes have minimal tides and little or no dynamic viability; thus, the spatial change in lake level closely follows the geoid. Many lakes are monitored so that changes in lake levels can be accounted for in the evaluation. Of course, there are some disadvantages. In general, the small size of lakes limit the available altimeter data. For the Great Lakes, this is not an issue because their number and large size provide a reasonable quantity of data, free of land contamination, Even the TMR, with its large footprint, supplies uncorrupted data for these passes. Another concern is that the sample is not global, but reflects only what is happening at a single geographical location. While this is true, the numerous passes over the Great Lakes do provide a unique view of the temporal variation of the performance of the altimeter system.

The specific aspects of the performance of TOPEX/POSEIDON altimeter system investigated in this study include the overall evaluation of the NASA altimeter, and comparisons of the NASA and CNES orbits, the wet tropospheric corrections, and the ionospheric corrections. In addition, an estimate of the relative bias between the NASA and CNES altimeters is obtained.

TOPEX/POSEIDON Overview

TOPEX/POSEIDON was launched on August 10, 1992. After a series of maneuvers that spanned nearly six weeks, the satellite was placed in its exact repeat operational orbit. The first 9.9-day repeat cycle commenced on September 22, 1992. The primary instrument on the satellite is the NASA duel frequency altimeter (ALT). With both Ku and C bands, the ALT provides a direct estimate of the ionospheric range delay. Sharing a common antenna with the ALT is the experimental CNES Ku band Solid-State Radar Altimeter (SSALT). The satellite also carries the TMR to provide an estimate of the wet tropospheric path delay. Three instruments are devoted to precision orbit determination. The Laser Retroreflector Array (LRA) is used with the laser ranging network to provide the NASA baseline tracking data, The CNES baseline tracking is obtained from their Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) dual-doppler tracking system receiver, which also gives ionospheric delay information. Finally, the Global Positioning System Demonstration Receiver(GPSDR) uses differential ranging for precise, continuous tracking of the spacecraft,

The common antenna shared by ALT and SSALT means that only one altimeter can be operating at a time. During the first 16 cycles, the CNES altimeter was operated, by pre-established agreement, during specific periods (amounting to approximately 12 percent of the data) in order to facilitate the cross-calibration of the altimeters, particularly at the

NASA and CNES verification sites (see Christensen et al., 1994). At the recommendation of the Science Working Team (SWT) at the Verification Workshop in February 1993, this plan was changed so that the CNES altimeter is on one complete cycle out of every ten, The new "Antenna Sharing Plan" was implemented on Cycle 17 and the first full SSALT cycle was Cycle 20.

TOPEX/POSEIDON Great Lakes Data

A total of 11 TOPEX/POSEIDON passes cross the Great Lakes during the satellite's 9.9-day exact repeat cycle. These passes are illustrated in Figure 1, Each lake is sampled by at least two passes. Not surprisingly, Lake Superior, the largest Great Lake, has the best coverage with six passes,

The TOPEX/POSEIDON Great Lakes data used in this study were obtained from two sources, covering different time periods, The analysis of the performance of the NASA ALT is based on a total of 32 cycles of Topex Geophysical Data Records (GDR) extending from Cycle 1 through Cycle 34, Cycles 20 and 31 were devoted to the operation of the SSALT and, thus, NASA ALT data were not available. The TOPEX GDR data were obtained via the Physical Oceanography Distributed Active Archive Center (PO.DAAC). While this is the longest duration TOPEX/POSEIDON data set available for analysis, it does not include the CNES SSALT data or the DORIS orbit and ionospheric delay data. These are provided on the Merged GDR produced by AVISO and PO.DAAC (see Benada, 1993). At the time of this analysis, only Cycles 7 through 30 were available in the Merged GDR format. Thus, the shorter Merged GDR data set was used for those evaluations requiring data not on the Topex GDRs.

The altimeter data extracted from the TOPEX GDRs and Merged GDRs consist of geolocated, one-second average height (lake level) estimates. The TOPEX GDRs and Merged GDRs include a variety of corrections and data-quality flags, which are discussed in detail by Callahan (1992) and Benada (1993). Only three conditions were placed on the NASA ALT data extracted over the Great Lakes from the TOPEX GDRs and Merged GDRs. First, as the purpose of this study is to evaluate different aspects of the altimeter system, all necessary data needed to perform these comparisons had to be available for each height estimate used, Second, the altimeter had to be operating with EML (early, middle, late) tracking, Third, the RMS of the ten-per-second height estimates, which are averaged to produce the one-second value, could not exceed 10.0 cm. The data selection for the CNES SSALT data from the Merged GDRs was based on the same criteria, except there is no flag indicating EML tracking, and the limit on the RMS of the height estimates was extended to 15.0 cm. (The RMS of the SSALT height estimates is often significantly higher than for the NASA ALT. Apparently, the SSALT values are calculated differently.) Other data flags were not used as a primary data selection criteria. Because of the relatively small data set, questionable data are easily identified and eliminated during the analysis.

The following corrections were applied to each height estimate: dry tropospheric, wet tropospheric (TMR or the French Meteorological Office [FMO] model, depending on the analysis), ionospheric (duel frequency ALT or DORIS depending on the analysis), solid Earth tide, pole tide, and the NASA EM bias.

Lake Level Data for the Great Lakes

Lake level data for these analyses were obtained from the Great Lakes Section, Ocean and Lake Levels Division, National Ocean Service (NOS). The Section is responsible for management of a permanent network of 49 lake level stations located throughout the Great Lakes Basin, including the connecting waterways and Lake St. Clair. Several stations have been in operation since the mid- 1800s. The data are used to support regulation, navigation and charting, river and harbor improvement, power generation, and scientific studies. All data are referenced to a common datum: International Great Lakes Datum (IGLD), which is also used by a comparable Canadian network of stations. Figure 2 shows the location of the NOAA stations on the Great Lakes and the selected stations used in this study.

The NOAA stations are each generally configured with a primary digital float-driven electromechanical gauge providing punched-paper-tape output. These gauges collect data at 15-minute intervals with 0.01-foot resolution and with a backup analog float-driven mechanical gauge collecting data on a strip chart with 0.01 resolution, A station observer makes daily checks on the systems for correct time and to make independent water level measurements using an electric-tape-gauge (ETG). The ETG observations are used to complete the editing and processing of the data and to ensure the data are continuously referenced to datum. The gauges are located in heated walk-in enclosures sitting on top of wells or sumps located several feet from the shoreline. The wells are connected to the water with underground horizontal intake pipes located at sufficient depth to be below the expected ice thicknesses. These configurations act as stilling wells for the high-frequency wind waves while allowing full transmission of the lake variation frequencies.

Using hourly data, the daily, monthly, and annual average water levels are computed for each station as standard output products. Highest and lowest daily average water levels for each month and frequency distributions of the daily average water levels are also compiled. For purposes of this paper, average daily lake levels for each lake were estimated by averaging the daily lake levels from several strategically spaced stations from each lake.

Figure 3 illustrates the consistency among stations on two of the five lakes. For each lake, the figure displays a time series of daily lake levels from the selected stations used in this study. The Lake Superior stations clearly display significantly better consistency than the Lake Erie stations, particularly during winter. The brief, but significant, departures from the mean trend by some or all of the Lake Erie stations are due to wind-driven events (e.g., seiche). Lake Erie is extremely susceptible to seiche action in which the basin is set into periodic 'slosh' motion in response to meteorological forcing. Stations on Lakes Michigan and Huron show consistency similar to Lake Superior. The agreement among the Lake Ontario stations is far superior to any of the other lakes. The error resulting from the Lake Erie seiches will be discussed later.

Data Analysis Methodology

In principle, evaluating a spaceborne altimeter system over a lake is straightforward. For a given pass over a given lake, a collinear analysis (e.g., Cheney, et al., 1983) is performed, evaluating the altimeter-derived lake level height variations as a function of time, Each overflight of the lake provides an estimate of the departure from the mean lake level. This departure also includes an estimate of the altimeter system error. As the lake level variation is known, it can be removed from the analysis and the residuals studied.

The collinear analysis procedure used in this study is summarized below. For each pass over a given lake, a series of O. OS-degree latitude bins are established. Ideally, a single one-second altimeter lake height estimate will fall into each latitude bin for every TOPEX/POSEIDON overflight. In reality, the amount of usable data varies from one overflight to the next. This produces variable length tracks over the lake. The analysis technique is designed account for this problem.

Defining $h(\phi,\xi,p,of)$ as a one-second altimeter lake level estimate made at latitude (ϕ) and longitude (ξ) on pass (p) during overflight number (of), the average lake level (h_{avg}) for a given latitude bin (ϕ_{bin}) is given by

$$h_{avg}(\varphi_{bin},p) = \frac{1}{n(\varphi_{bin},p)} \sum_{1}^{n(\varphi_{bin},p)} h(\varphi,\xi,p,of) \qquad (1)$$

where $n(\phi_{bin},p)$ is the total number of altimeter lake level estimates falling in latitude bin, ϕ_{bin}, for all overflights of pass, p. The equivalent expression for the average geoid height (g_{avg}) of the bin is

$$g_{avg}(\varphi_{bin}, p) = \frac{1}{n(\varphi_{bin}, p)} \cdot \sum_{1}^{n(\varphi_{bin}, p)} g(\varphi, \xi, p) \tag{2}$$

where $g(\phi,\xi,p)$ is also provided on the GDR.

A minimum of four latitude bins across the lake must have observations for a given overflight to be considered in the analysis. The selection of the minimum number of bins has an impact on the final number of overflights used in the analysis. Allowing too few bins may result in a few poorly represented overflights substantially increasing the overall RMS error. Limiting the analysis to only those overflights with a large number of latitude bins significantly reduces the number of available overflights, The four bin requirement -strikes a satisfactory balance. It permits every pass over all five lakes to be used and it does not significantly change the RMS error.

Another requirement is that each latitude bin must have observations from a minimum of three overflights for that bin to be included in the analysis. This minimum is a small number of overflights when compared to the maximum possible of 32 (cycles) used in the Topex GDR analysis. However, some passes are missing overflights due to the CNES SSALT being on, missing TMR data, or other reasons. These problems are compounded in the Merged GDR analysis, which includes eight less cycles of data. There are a few very short passes (such as Pass 152 over Lake Superior) for which excluding bins with only a few overflights would significantly reduce the number of overflights available. A weighting procedure is included in the analysis (see equation 4 below) so that latitude bins with more data are given a proportionally greater weight in establishing the average departure from the mean lake level. This procedure provides the maximum temporal resolution (greater number of overflights) while producing accurate results.

After the average lake level and geoid values are determined for each bin, the residuals, Ah, are calculated for a each overflight. The overflight residuals are corrected to the location of the bin average using the known geoid variation as shown below.

$$\Delta h(\varphi_{bin}, p, of) = h(\varphi, \xi, p, of) - h_{avg}(\varphi_{bin}, p) - (g(\varphi, \xi, p) - g(\varphi_{bin}, p)) \quad (3)$$

For a given overflight, the weighted average departure from the mean lake level, Δh_{avg}, is determined using

$$\Delta h_{avg}(p, of) = \frac{1}{\sum_{1}^{n_o(p,\, of)} n(\varphi_{bin}, p)} \sum_{1}^{n_o(p,of)} \Delta h(\varphi_{bin}, p, of)\, n(\varphi_{bin}, p) \quad (4)$$

where $n_o(p,of)$ is the number of one-second altimeter observations in a given overflight. It should be noted that n_o is usually equal to the number of latitude bins. However, for TOPEX/POSEIDON, the latitude spacing of the footprints is slightly smaller than the size of the latitude bins. Thus, it is possible to have two observations in a given bin for a single overflight.

For each overflight, corrected residuals Δh_{res} are obtained by removing the average departure from the mean lake level.

$$\Delta h_{res}(\varphi_{bin}, p, of) = \Delta h(\varphi_{bin}, p, of) - \Delta h_{avg}(p, of) \qquad (5)$$

The Δh_{res} values are combined for all overflights for that pass and examined (as a function of latitude) for "trends" and "blunder points" or outliers. The blunder points typically occur near land and are the result of land contamination. For this study, the one-second observations were considered outliers and edited from the data if Δh_{res} was more than ± 15 cm. The vast majority of the observations have Δh_{res} values of within ± 5 cm. After editing, the analysis procedure (Equations 1-5) is redone with the edited data set.

Trends, affecting one or more latitude bins, in the cross-lake Δh_{res} values can occur due to quirks in the data distribution among the latitude bins. The trends, when observed, are usually near land where fewer observations are available and reflect errors in the mean lake level for the latitude bins in question. Trends of this type were more of a problem with Geosat (Morris and Gill, 1994) than TOPEX/POSEIDON. The weighting procedure utilized minimizes the importance of these bins. However, it is possible to improve the lake level means by using the information provided by Δh_{res}. This can be done because the relative variation of lake level across the lake is typically static, a condition not true of the ocean. Thus, the average value of Δh_{res} for each bin should be zero, if the mean lake level for that bin, relative to the other mean lake level values along the pass, is correctly determined. A non-zero mean for the Δh_{res} implies that the average lake level is in error by approximately that amount. By correcting to the average lake level for the bin in question, an improved spatial variation of lake level along the satellite groundtrack is obtained (Morris and Gill, 1994, Figure 4). This procedure is summarized by Equations 6 and 7.

$$h_{avg}cor(\varphi_{bin}, p) = \frac{1}{n(\varphi_{bin}, p)} \sum_{1}^{n(\varphi_{bin}, p)} \Delta h_{res}(\varphi_{bin}, p, of) \qquad (6)$$

$$h_{avg}(\varphi_{bin}, p) = h_{avg}(\varphi_{bin}, p) - h_{avg}cor(\varphi_{bin}, p) \qquad (7)$$

The entire analysis procedure is then repeated with the new h_{avg} values.

The final step to obtain a complete time series of Δh_{avg} values for a given lake is to combine the results from the different passes. This is done assuming that the temporal lake level variations are the same over the entire lake, an assumption which is consistent with the NOAA/NOS lake level measurements (eg., Figure 2). For a given pass, the sum of the time series of Δh_{avg} values equals zero. To combine the different passes having different temporal distributions of overflights, all passes are referenced to the pass with the greatest number of overflights (the base pass). For a given pass (p), this is accomplished by interpolating the base pass Δh_{avg} to the overflight times of pass (p) and minimizing the sum of the squares between pass (p) and the base pass. This procedure results in an average offset value for pass (p), which is then applied to all of the pass (p) Δh_{avg} values, Thus,

$$'h\ final\ (p, 'f) = \Delta H_{avg}(p, 'f) + of\ f\ se\ t_{pass}(p) \qquad (8)$$

The daily average NOAA/NOS lake level measurements ($lake_{meas}$) for the lake in question are interpolated to the time of each Δh_{final} value. Anaverage offset between the lake level measurements and the Δh_{final} values ($offset_{lake}$) is determined by minimizing the sum of the squares. The altimeter residual (ALT_{res}), the estimate of the error in the altimeter system measurement for a given lake (L), pass (p), and overflight (of), is given by

$$ALT_{res}(L,P,of) = \Delta h_{final}(p,of) - (lake_{meas}(L,of) - offset_{lake}(L)) \quad (9)$$

By directly combining ALT_{res} values from different overflights, passes, and lakes, a time series of the estimated altimeter error as a function of time can be obtained, By smoothing these estimates (e.g., with a simple five point running mean or by cycle), significant features can be seen. For Geosat (Morris and Gill, 1994), an annual cycle superimposed on a trend in the residuals was discovered. Orbital maneuvers are also detectable, both in Geosat and with the preliminary orbit in the Topex **Interim GDRs.** (Note that orbital maneuvers are not apparent in the Topex GDRs because of the methodology used to process the final orbit.)

Evaluation of the Altimeter System

The NASA Altimeter

The primary altimeter system onboard TOPEX/POSEIDON is the NASA ALT. It is expected that the best estimates of sea surface height will be obtained when the NASA ALT measurements are corrected for the wet tropospheric delay and ionospheric delay, using TMR and the dual-frequency altimeter values, respectively. This is our baseline case. Thirty-two cycles of Great Lakes data spanning Cycles 1-34 were extracted from the TOPEX GDRs, which only includes the NASA POE orbit.

Using the methodology discussed above, passes over each of the five lakes were analyzed. Table 1 summarizes the resulting RMS error derived for each lake. While four of the lakes give reasonably consistent results, Lake Erie stands out as a problem. Figure 4 shows TOPEX/POSEIDON estimates compared within situ measurements of lake level variation for Lake Superior and Lake Erie. This figure illustrates that the large RMS value for Lake Erie is generated only during the winter when the seiches occur (see ‘Figure 3) and the in situ lake level measurements are inconsistent, Lake Superior, by comparison, has no such problem. After the gap in the Lake Erie data, which is the result of lake ice and SSALT Cycle 20, the TOPEX/POSEIDON and measured lake level variation display excellent agreement. In fact, the RMS is just 3.8 cm for that period ($\geq$ Cycle 21) as compared to 8.0 cm for the entire period. Based on these findings, only this latter portion of the Lake Erie data was included in the evaluations,

Figure 5a displays the final altimeter residuals (ALT_{res}) averaged over each cycle. The average RMS error is 4,44 cm, based on 382 overflights of the Great Lakes. A least squares fit of the individual altimeter residuals suggests a slightly negative trend in the residuals of -1.0 ($\pm$ 0.8) cm/year. This trend is misleading because it is known that the first three cycles had particularly bad nadir pointing, which could result in an error in the altimeter height estimates. Not including the first three cycles eliminates any significant trend (+0.3 $\pm$ 0.9 cm/year) and slightly decreases the RMS to 4.37 cm. Thus, there is no obvious long-term drift in the altimeter system.

In order to investigate possible periods in the residuals, a power spectrum was computed. A five-point running mean time series was constructed from the individual ALT_{res}. Residual values for every 0.5 days were then obtained by using cubic spline interpolation. The power spectrum was then calculated from the equally spaced, interpolated residuals. The resulting power spectrum is shown in Figure 6. The most significant feature of the power spectrum is a maximum, corresponding to a period in the residuals of 56 ($\pm$5) days. This correlates closely with the synodic period of the satellite and suggests the possibility that some of the forces are not modeled perfectly in the orbit ' analysis. This periodic variation is also apparent in Figure 5a.

Figure 5C (solid line) shows the computed RMS for each cycle. The largest error occurs during Cycle 10, which had poor tracking because of the end-of-the-year holidays. There are no particular trends in the RMS error. There is also no correlation between the cycle RMS value and the average residual (Figure 5a).

The number of overflights used in the analysis varied significantly (Figure 5d). Prior to Cycle 17, the SSALT altimeter was on for some of the passes (except for Cycles 7 and 10). In addition, the Lake Erie data were not included during this period because of the problems with the seiche. There is a downward trend in the number of overflights between Cycles 11 and 19. This is due to the increase in lake ice during the winter season. Beginning with Cycle 21, the lake ice was gone or disappearing and the Lake Erie data were added, This resulted in the number of usable overflights increasing to near the maximum number (18). There is no obvious correlation between the number of overflights and the average residuals (Figure 5a) or the average RMS (Figure 5c).

TMR vs. FMO Wet Tropospheric Correction

Using the same 32-cycle data set, the FMO model-derived wet tropospheric path delay correction was substituted for the TMR correction. The residuals by cycles are shown in Figure 5b. Unlike the TMR results (Figure 5a), the FMO correction produces a distinct long-term trend in the residuals. Although not quite a year of data is used in this analysis, Figure 5b strongly suggests that the FMO residuals display an annual cycle with a minimum in early spring and a maximum in the fall. Assuming this is an annual cycle, 'it is similar to the one found for Geosat (Tapley et al., 1992; Morris and Gill, 1994), except that the phase is different.

The variation of RMS with cycle is shown in Figure 5c (dashed line). When compared with the FMO RMS (solid line), the corrections are in good agreement during the cool, dry winter (Cycles 8- 18) when the wet tropospheric correction is very small. However, during the summer the RMS error can differ by a factor of two. In all, the FMO correction produces an overall RMS error of 5.97 cm as compared with the 4.44 cm found using TMR. This implies that, on average, using the TMR improves the altimeter height estimate by 4.0 cm.

Dual-frequency vs. DORIS Ionospheric Correction

This comparison was done using the 24 cycles of data (Cycles 7-30) available in the Merged GDR format, which included the DORIS ionospheric correction and the CNES orbit, which was also derived from DORIS observations. Based on 268 overflights, the average RMS error, using the NASA ALT, TMR. NASA POE orbit, and the dual-frequency ionospheric correction, is 4.47 cm, When the DORIS correction is substituted, the RMS increases to 4.68 cm. This amounts to an average improvement of 1.4 cm using the dual-frequency correction.

While the dual-frequency correction, on average, is only marginally better than the DORIS correction, this difference was consistent over each lake. In addition, it must be remembered that the ionospheric correction is relatively small in the mid-latitudes (Imel, 1994). The greatest error should occur where the values of the correction are the greatest, ‘near the equator.

NASA POE vs. CNES DORIS Orbit

Using the 24 cycles of Merged GDR data, the CNES orbit gives an RMS of 4.31 cm. When compared to the NASA POE RMS of 4.47 cm, there is an average improvement of 1.2 cm. While marginal, this difference was consistent over four of the five lakes.

Discussion

The RMS errors quoted above are upper limits for the altimeter system. The other source of error is the in situ lake level measurements. How representative is the average in situ lake level, determined from near-shore stations, when compared to an instantaneous altimeter measurement, with a footprint size of several kilometers, in the middle of the lake? We don ‘t have a definitive answer. However, the in situ lake level error averaged along the altimeter groundtrack must be much less than four centimeters. Otherwise, the RMS error seen in these analyses would be larger. The Lake Erie seiche events gives an indication of what can happen when the lake level measurement is not representative of the portion of the lake that the altimeter is observing (Figures 3 and 4).

The typical RMS difference between a single in situ lake level station and the average of all the selected stations is less than three centimeters (less than two for Lake Ontario). These statistics are based on daily, not instantaneous, averages. However, based on the slow temporal change in lake level and the fact that the altimeter measurement covers several kilometers, three or four centimeters is a reasonable RMS difference to expect between the actual lake level in the middle of the lake and what would be expected based on the average in situ measurement. This error will be reduced as the altimeter sampling across the lake is increased. Based on this reasoning, we believe that the typical RMS error contributed by the in situ measurements is between one and two centimeters. Accounting for this error source reduces the altimeter system error from 4.4 cm to about 4.0 cm.

Determination of the Relative Bias Between the NASA and CNES Altimeters

A total of 19 SSALT overflights have sufficient data for analysis. This is too limited a sample to permit a direct assessment of the CNES altimeter. However, an estimate of the relative bias can be obtained. This quantity is of interest because of the desire to combine the ALT and SSALT data to create a complete time series.

Methodology

The data selected for the relative bias calculation were extracted from the Merged GDR. Because the dual-frequency ionospheric correction is not available for the SSALT data, the DORIS correction was used with both the NASA ALT and CNES SSALT observations for consistency, The TMR correction was adopted for all the data. Any height estimates not having all the appropriate corrections were eliminated from the analysis.

Ideally, the relative bias for a given pass over a given lake is obtained by subtracting the S SALT h_{avg} (from Equation 1) from the ALT h_{avg} values and correcting for differences in the lake level. With the large number of NASA ALT overflights, the ALT h_{avg} values are well determined. This is not true for the SSALT h_{avg} because of the small number of overflights available, Instead of using the SSALT h_{avg} values, the individual overflight data were analyzed.

For each pass over a lake, the ALT h_{avg} values are determined as a function of latitude, as with the previous analyses. For each valid SSALT one-second observation, $h(\phi,\xi,p,of)$, the ALT h_{avg} values are interpolated to ϕ. The relative bias between the interpolated ALT h_{avg} and SSALT $h(\phi,\xi,p,of)$ values is found by minimizing the sum of the squares of the differences. The bias is then corrected for the variation of the lake level.

Relative Bias Results

Table 2 lists the relative bias values obtained for each SSALT overflight. There is a wide spread of values from -5.7 cm to -25.5 cm. The average of the 19 values is -16.6 cm with a standard deviation of 6.6 cm. The negative value indicates that the NASA ALT is measuring short relative to the SSALT. Restricting the average to best-determined overflights, those with ten or more SSALT observations, the average of the remaining nine estimates becomes -18.0 cm with a standard deviation of 6.8 cm. This is the value we adopt. A more precisely determined relative bias requires many more SSALT overflights,

Summary

We have presented an evaluation of the TOPEX/POSEIDON altimeter system over the Great Lakes. By all measures, unprecedented accuracy for a satellite altimeter system is being achieved with an RMS error of 4.4 cm or less. There is no evidence of a long-terrn drift in the system. However, the residuals do indicate a small-amplitude, systematic variation with a period of about 56 days that appears to be correlated with the synodic period of the satellite.

The analysis of corrections indicated that direct measurements by the satellite outperform model-derived estimates. This is particularly true of the wet tropospheric correction where the TMR provides an average improvement of four centimeters over the FMO model correction. The improvement shown by the dual-frequency ionospheric correction was marginal, but significant when compared to the DORIS correction.

The difference between the NASA POE and CNES orbits was also marginal. Overall, the CNES orbit gives slightly smaller residuals.

The lakes analysis also provided the opportunity to estimate the relative bias between the altimeters. Based on relatively few SSALT passes over the Great Lakes, the ALT was found to measure short, relative to the SSALT, by about 18 cm.

The final conclusion that can be drawn from these analyses is that the Great Lakes (or other lakes with in situ data) provide an excellent location to evaluate and monitor the performance of an altimeter system. We urge current and future projects to include these "non-ocean" data in their GDRs.

Acknowledgements. We thank Akiko Hayashi, JPL, for providing the reader for the 'Merged GDR. This work was performed, in part, at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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Figure Captions

Figure 1 — The distribution of TOPEX/POSEIDON NASA altimeter data used in the study. Pass numbers are indicated. Significant breaks in the data typically indicate the presence of an island.

Figure 2 — Distribution of NOAA/NOS lake level stations (boxes) along the Great Lakes. The subset of stations used in the analysis is denoted by a filled box.

Figure 3 — Examples of lake level measurement consistency: a) five stations on Lake Superior, and b) five stations on Lake Erie. Values are referenced to the IGLD. Observed departures in the Lake Erie data result from wind-driven events.

Figure 4 — Estimated relative lake level variation (NASA ALT, TMR, NASA POE) for (a) Lake Superior and (b) Erie. TOPEX/POSEIDON observations are denoted by pluses. Measured lake level variation is indicated by the solid line.

Figure 5 — a) Average NASA ALT residuals using TMR wet tropospheric correction as function of TOPEX/POSEIDON cycle. The gaps at Cycles 20 and 31 occur because the SSALT was operating for the entire cycle. b) Same as (a) except using the FMO wet tropospheric correction, c) RMS error as a function of TOPEX/POSEIDON cycle for the NASA ALT using the TMR

	(solid line) and FMO (dashed line). d) The number of TOPEX/POSEIDON ALT overflights used in the analysis as a function of cycle.
Figure 6	Power spectrum of NASA ALT residuals (see text for discussion). Peak represents a period of 56 ($\pm$5) days.

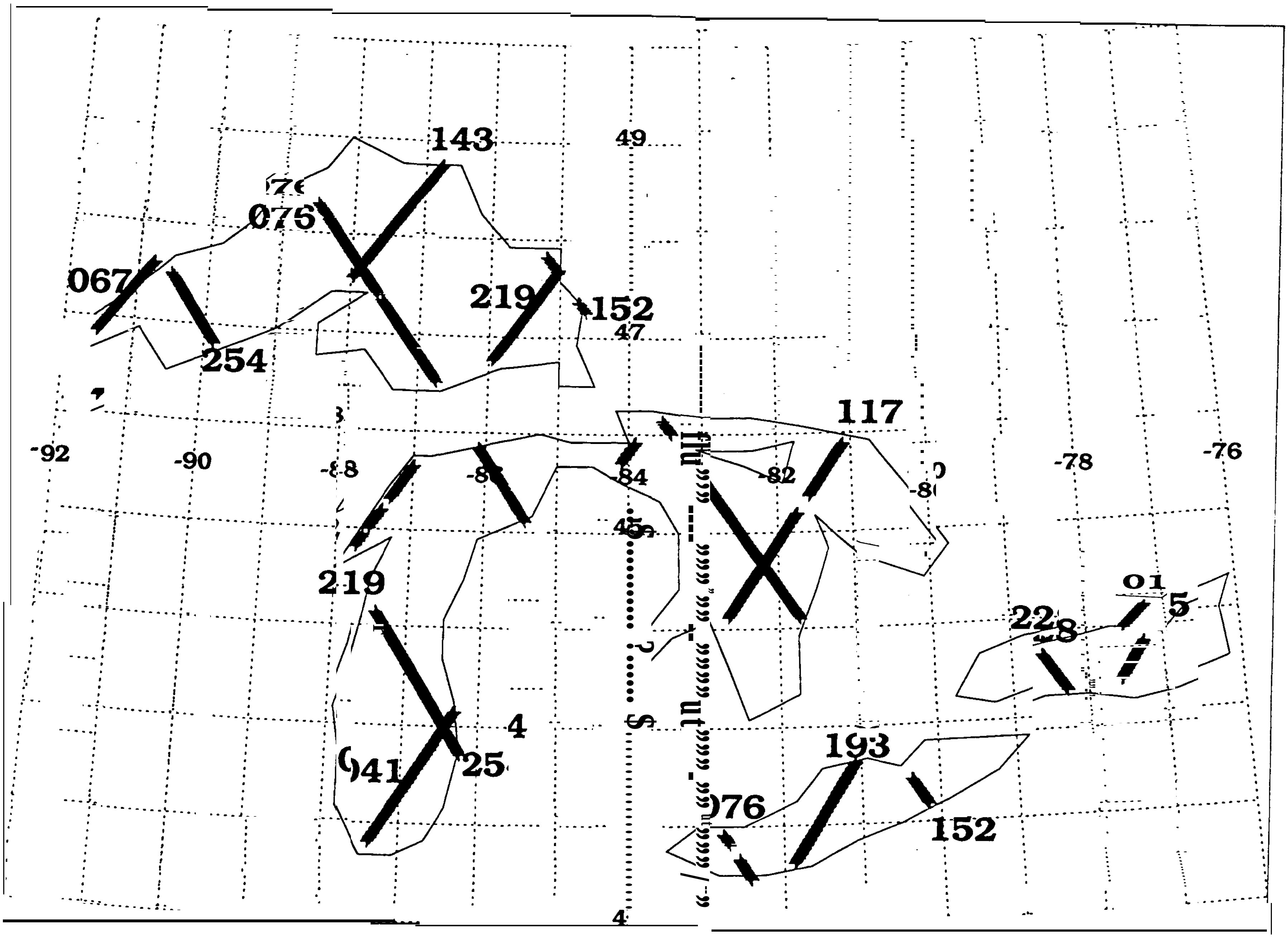
Table 1. Summary of Results for Individual Lakes

(NASA ALT, TMR, NASA POE)

Lake	RMS (cm)	Number of Overflights
Superior	4.28	136
Michigan	5.01	93
Huron	4.38	74
Ontario	4,19	44
Erie	8.01	70
Erie ($\geq$ Cycle 21)	3.78	35

Table 2. Relative Bias Between the NASA and CNES Altimeters

Pass/Lake	Cycle	Bias (cm)	Number of SSALT Observations
015/Ontario	14	-24.7	6
041/Michigan	9	-19.9	15
	12	-16.9	1 2
	14	-25,5	6
	16	-22.1	10
	20	-8.4	7
‘076/Superior	20	-23.6	25
1 17/Huron	20	-18.9	5
193/Erie	20	-18.0	10
219/Michigan	8	-16.7	6
219/Superior	7	-16.1	7
228/Ontario	8	-5.7	5
	11	-6.7	6
	12	-13.3	5
254/Michigan	8	-18.4	13
	13	-17,3	4
	20	-14.4	18
254/Superior	8	-16.2	11
	20	-12,6	11



143
49
076
067
219
152
47
254
117
-92
-90
-84
-82
-78
-76
219
22
01
5
4
941
25
193
076
152

Fig. 1

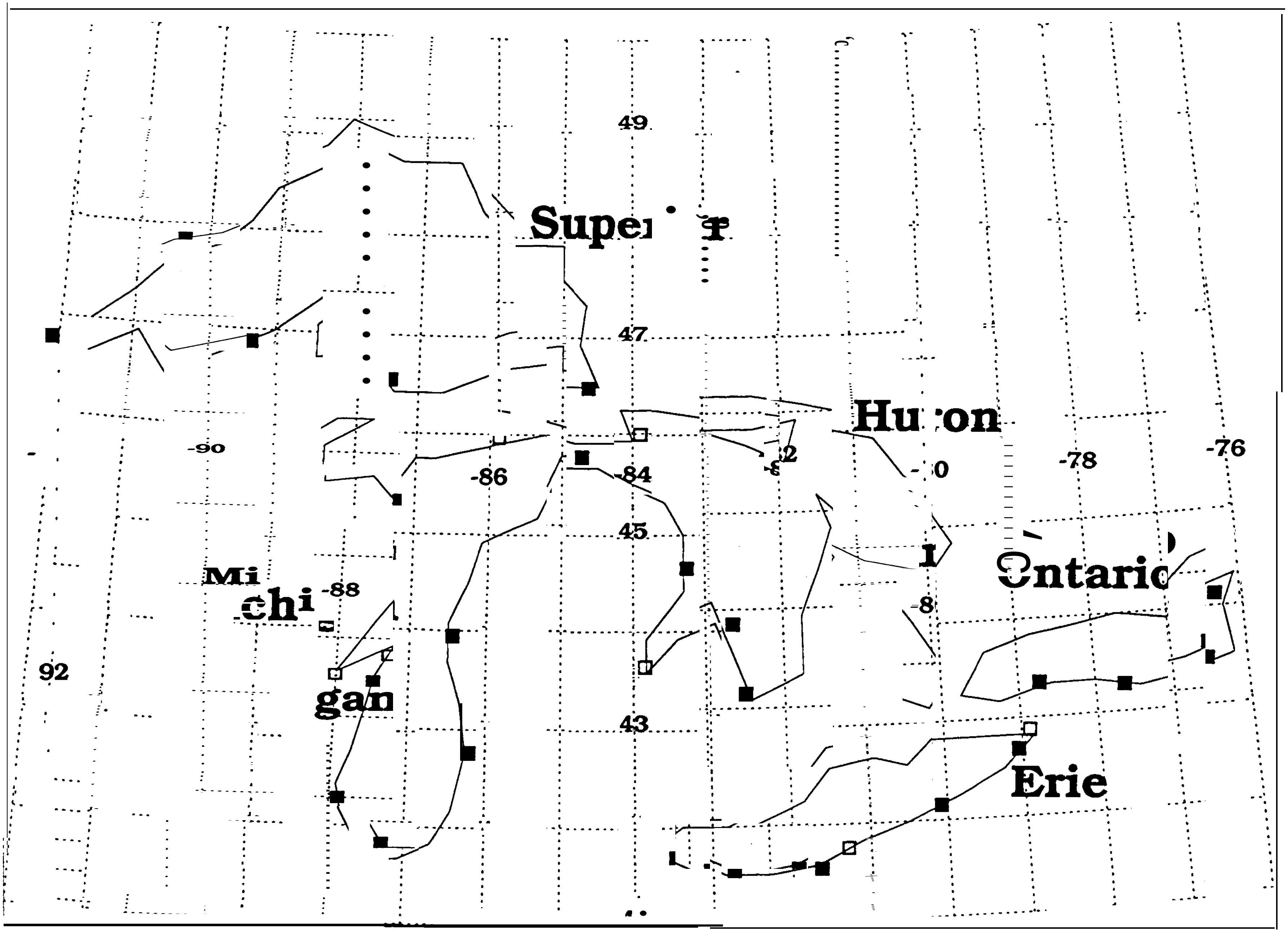


Fig. 2

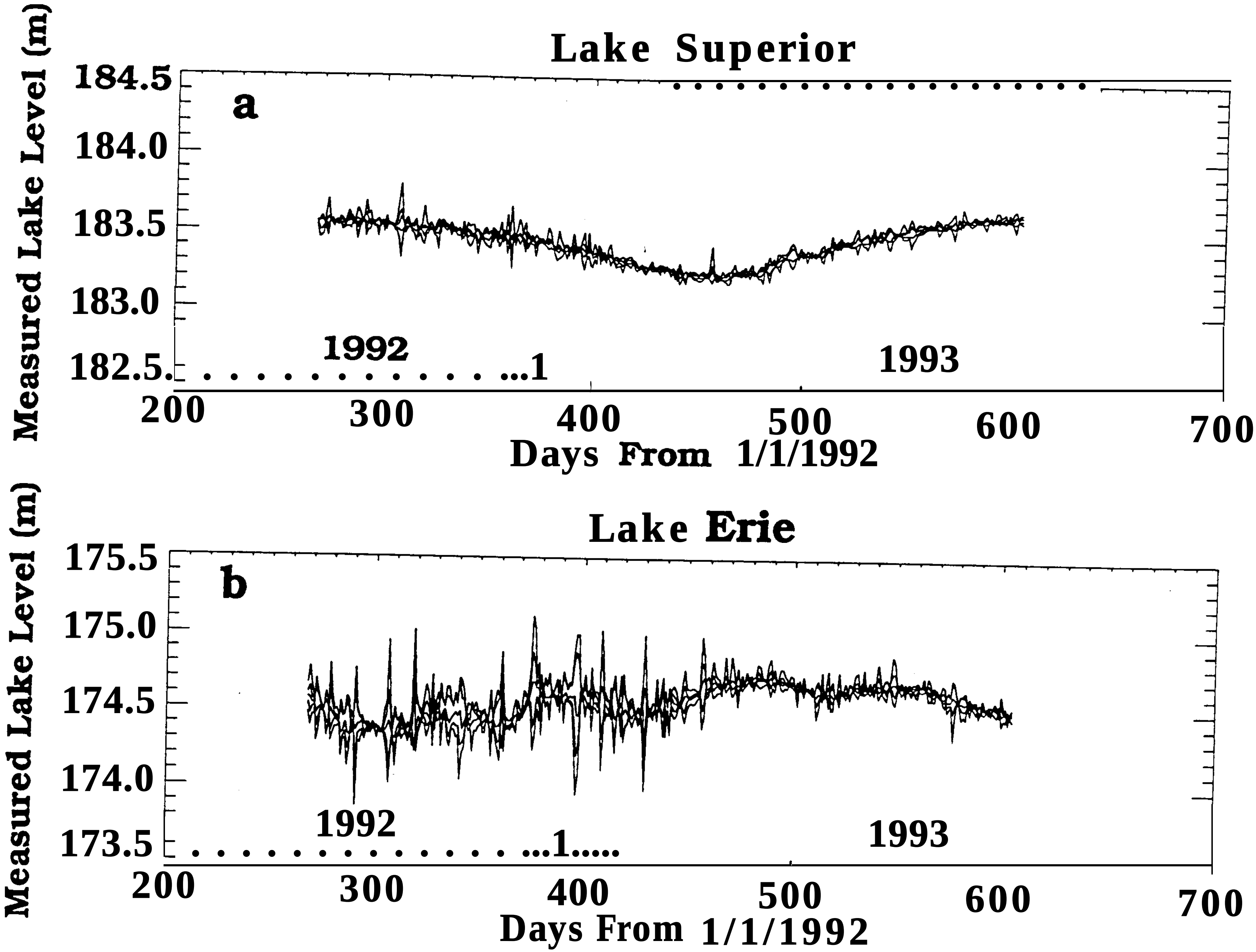

Lake Superior
a
Measured Lake Level (m)
184.5
184.0
183.5
183.0
182.5
1992
1993
200
300
400
500
600
700
Days From 1/1/1992
Lake Erie
b
Measured Lake Level (m)
175.5
175.0
174.5
174.0
173.5
1992
1993
200
300
400
500
600
700
Days From 1/1/1992

Fig. 3

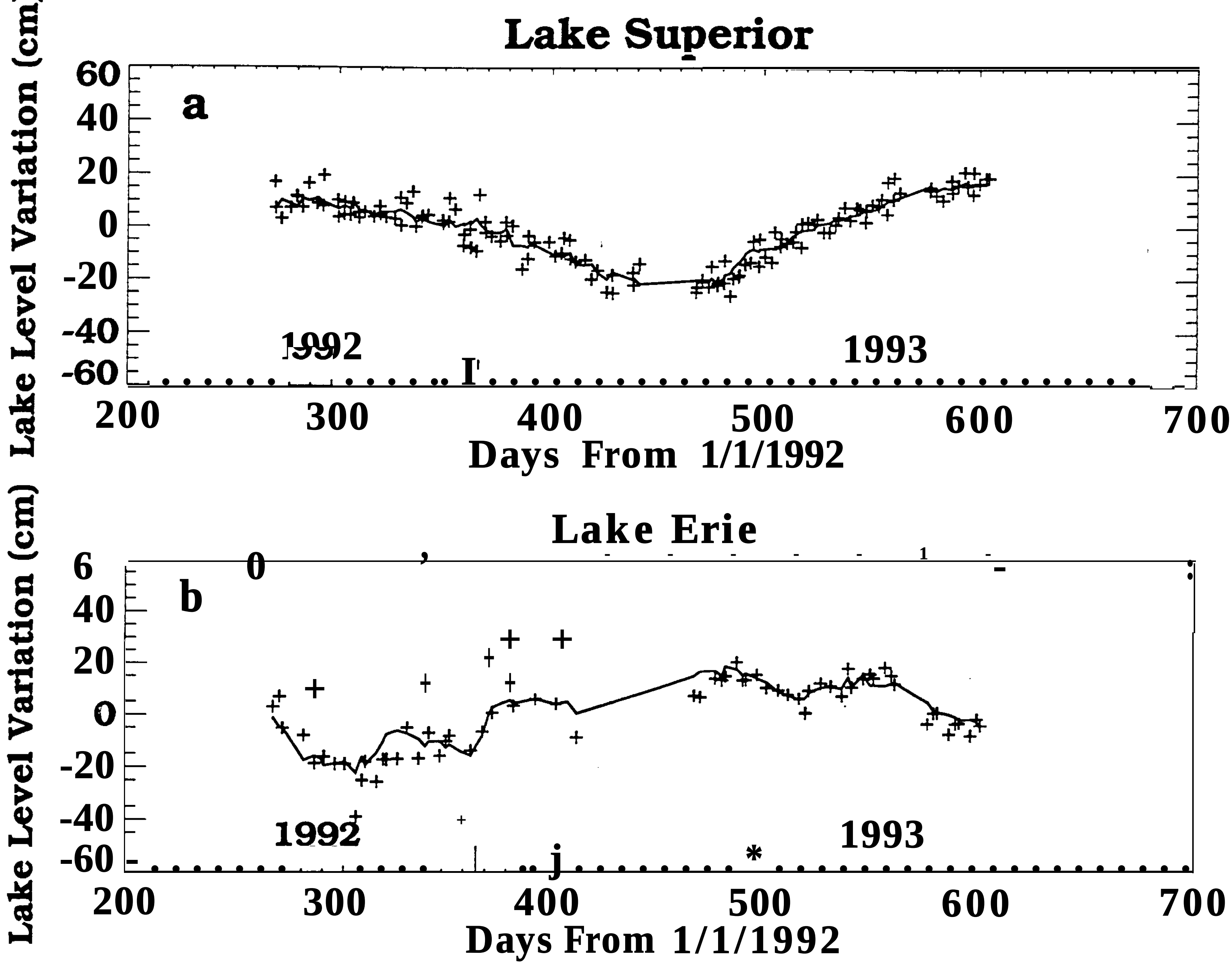

Lake Superior
a
Lake Level Variation (cm)
60
40
20
0
-20
-40
-60
1992
1993
200
300
400
500
600
700
Days From 1/1/1992
Lake Erie
b
Lake Level Variation (cm)
6
40
20
0
-20
-40
-60
1992
1993
200
300
400
500
600
700
Days From 1/1/1992

Fig. 4

Fig. 5

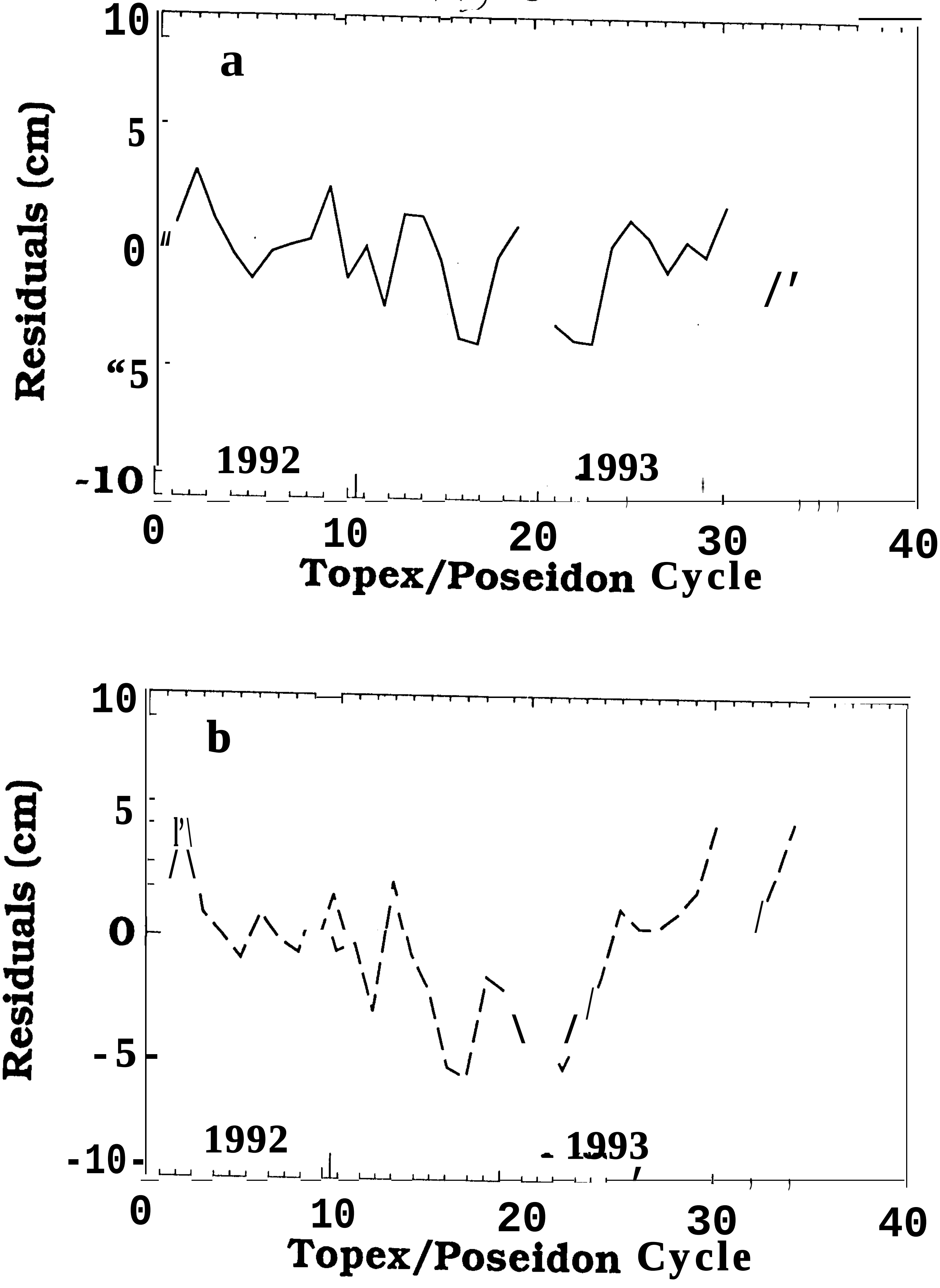
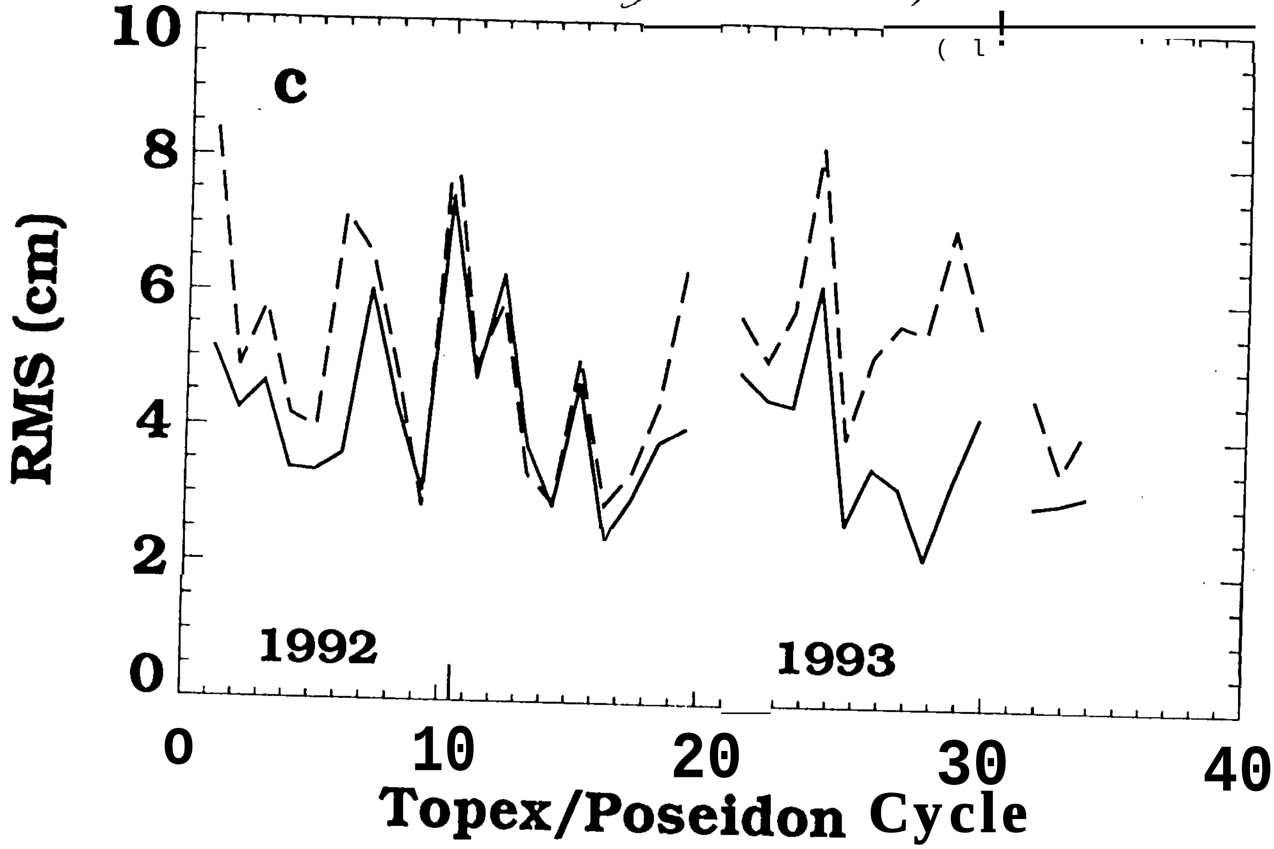
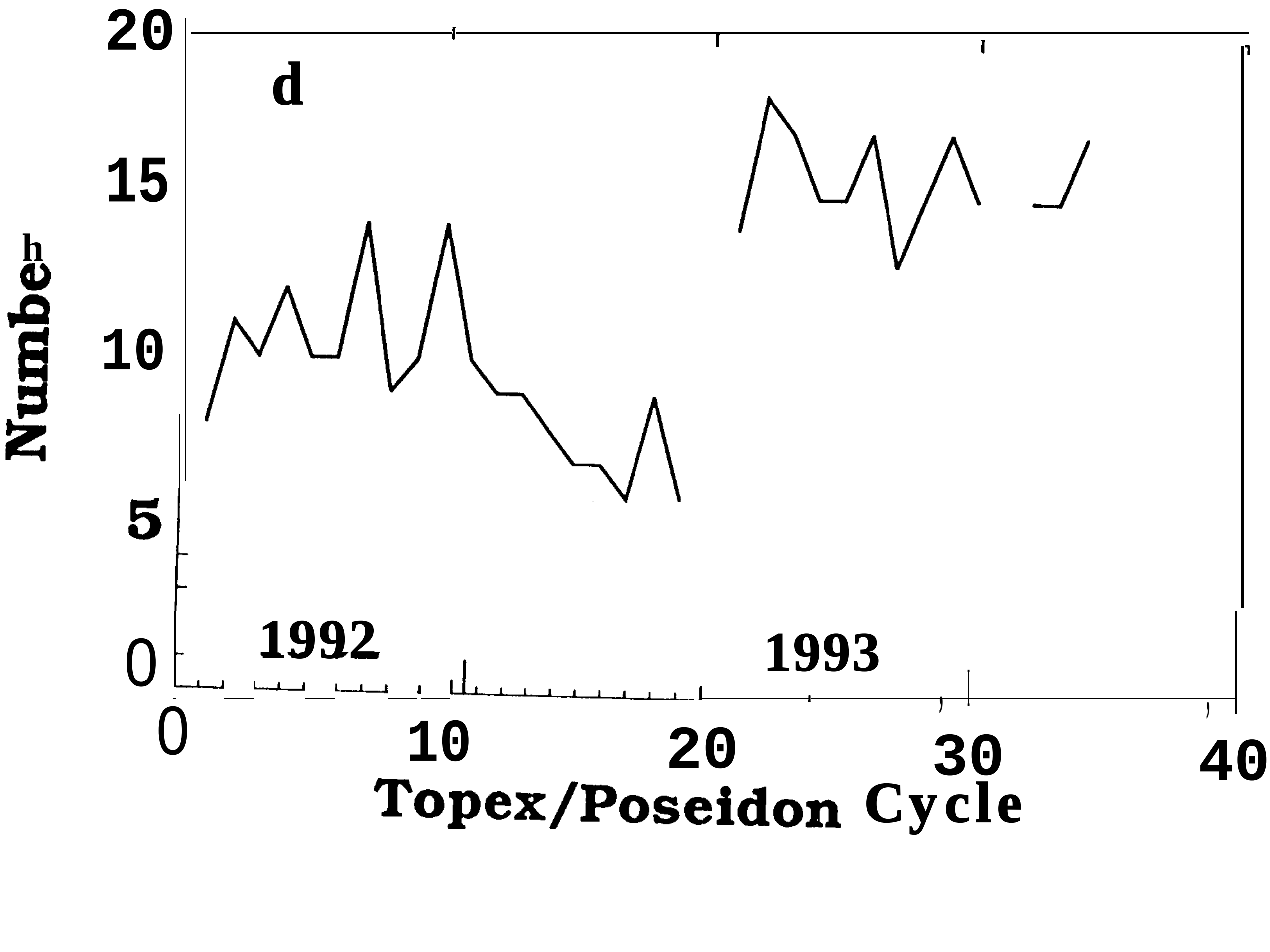

a
Residuals (cm)
10
5
0
-5
-10
1992
1993
0
10
20
30
40
Topex/Poseidon Cycle
b
Residuals (cm)
10
5
0
-5
-10
1992
1993
0
10
20
30
40
Topex/Poseidon Cycle

Fig. 5 (cont.)


c
RMS (cm)
10
8
6
4
2
0
1992
1993
0
10
20
30
40
Topex/Poseidon Cycle


d
Number
20
15
10
5
0
1992
1993
0
10
20
30
40
Topex/Poseidon Cycle

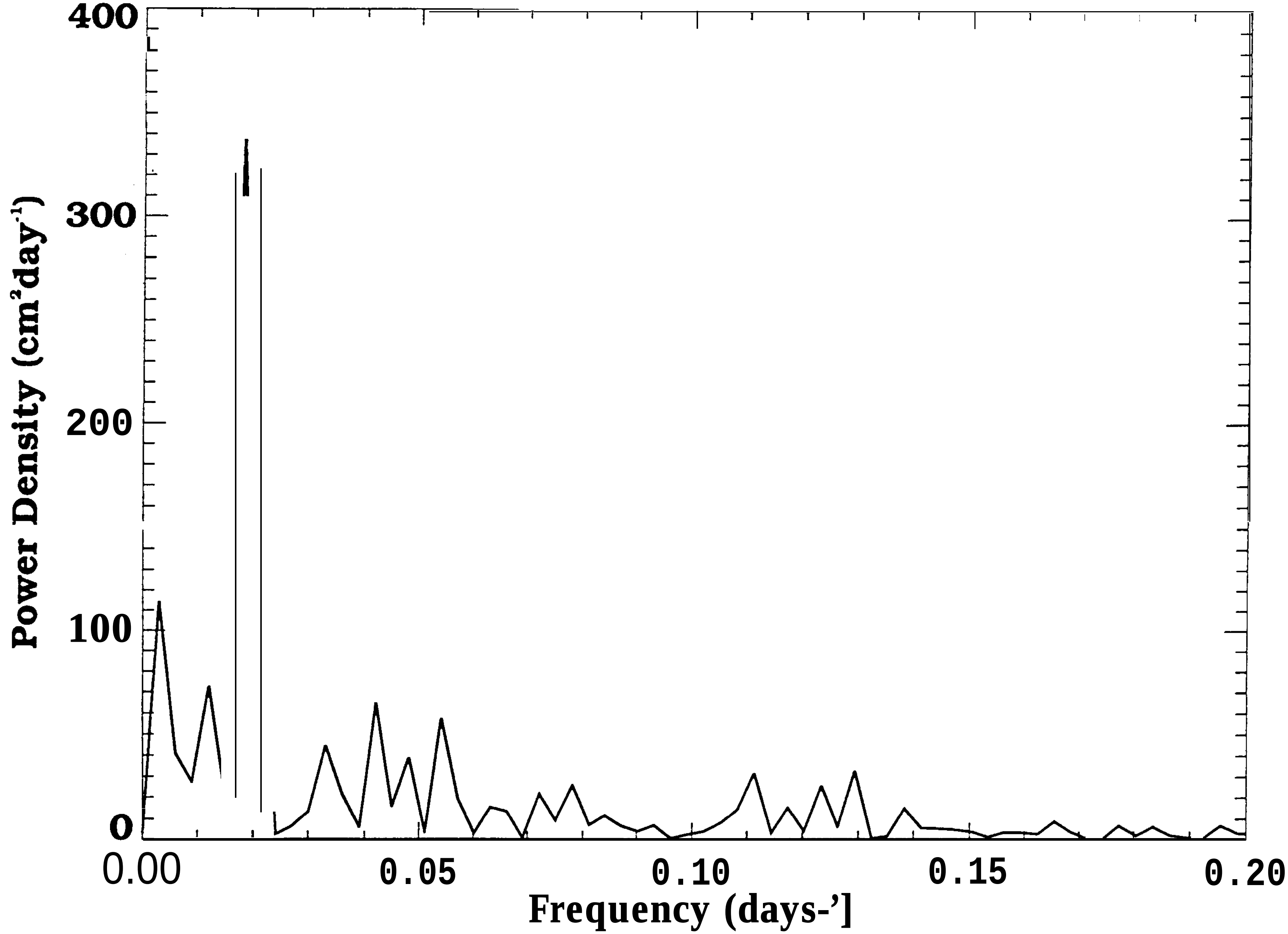

400
300
200
100
0
Power Density (cm²day⁻¹)
0.00
0.05
0.10
0.15
0.20
Frequency (days-']

Fig. 6